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Experimental study on drag reduction in a duct

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Abstract: The present study investigates drag forces on liquids pumped through a duct coated with a magnetic liquid of kinematic viscosity of 1.69cSt. Due to a suitable arrangement of a set of permanent magnets, the magnetic liquid formed a fluid layer on the bottom of a square duct through which a silicone oil with a kinematic viscosity of 50cst was pumped. Applied magnetic flux densities ranged from less than 0.01T to about 0.15T at the surface of the magnets. The influences of the strength and gradient of the magnetic field, and of the fluid flow rate, on the shape of the magnetic fluid have been investigated. It was found that it is not practical to form a uniform magnetic fluid layer under our experimental conditions, and consequently the drag was increased compared to the uncoated case because the flow of the silicone fluid over the magnetic fluid layer deformed this layer dramatically. For a viscosity ratio between the main flow and the ferrofluid less than about 30, it is therefore not feasible to use a magnetic fluid layer to reduce the drag in a duct. However, it is possible that the generally high thermal conductivity of magnetic liquids, its convection, and interface deformation, might be exploited for heat transfer enhancement.

Key words: Drag reduction, magnetic fluid, magnetic field, fluids interface

1. INTRODUCTION

Theoretical analysis indicates that drag on a highly viscous fluid transported in a duct can be reduced by using a layer of a low-viscosity magnetic liquid, or 'ferrofluid', on the inner walls of the duct when the viscosity of the main fluid is at least four times that of the ferrofluid[1,2,3]. Such a layer can also be used for heat transfer enhancement as has been shown in earlier studies[2,4]. Deformation of the fluid interface has also been studied[5]. Nevertheless, convincing experimental results on drag reduction have not been seen. The present study investigates drag forces on liquids pumped through a ferrofluid-coated duct. Attention is focused on the dependence of interface shape and drag on the strength and gradient of the magnetic field, and the fluid flow rate.

2. EXPERIMENTAL DEVICES

To observe the shape of the magnetic fluid layer at different flow rates and in different magnetic fields, a flow system as illustrated in Figure 1 was built. An internal gear pump supplying up to 30 l min^{-1} at 1420 rpm, driven by an electric motor, 1.5 kW, 380/415 Volts, 3 phase, 50 Hz, was used to pump a silicone fluid through the pipe system. An inbuilt inverter/controller was adopted for varying the motor speed to adjust the flow rate in the measuring section. A bypass pipe added an additional means for adjusting the flow rate and ensured the integrity of the piping system. The flow rate was measured by a flow-measuring-unit that used a timer-controlled solenoid to divert the flow to a graduated cylinder. The volume of fluid collected was divided by the time set on the timer to get the flow rate. The test section was a 1000mm long duct made of Perspex with a 10mm square cross-section, the top of which could be opened for adding magnetic fluid. A differential pressure manometer was used to measure the pressure drop in the test section. Various sets of permanent magnets were installed under the test section to generate a variety of magnetic fields. The shapes of the interfaces were recorded by a camera.

Preliminary experiments with flexible magnets containing rubber with a strength at the surface of less than 6.3×10^{-2}T failed to hold the magnetic fluid onto the bottom of the duct even at the smallest measurable flow rate of about 0.2 ml s^{-1} (Results not shown). In a second series of experiments, a set of magnets was used, with each magnet 6 mm thick with pole faces 25 mm long and 19 mm wide and a maximum magnetic flux density of 0.11T at the surface. Six combinations of the magnets, as shown in Figure 2 (a) to (f), were used to change the strength and spatial gradient of the magnetic fields. Finally, a set of magnetic bars, 25 mm thick with pole faces 152 mm long by 25 mm, with a magnetic flux density of 0.15T at the surface, was used to produce the magnetic fields shown in Figure 2 (g), (h) and (i). Altogether, nine kinds of magnetic fields were used.

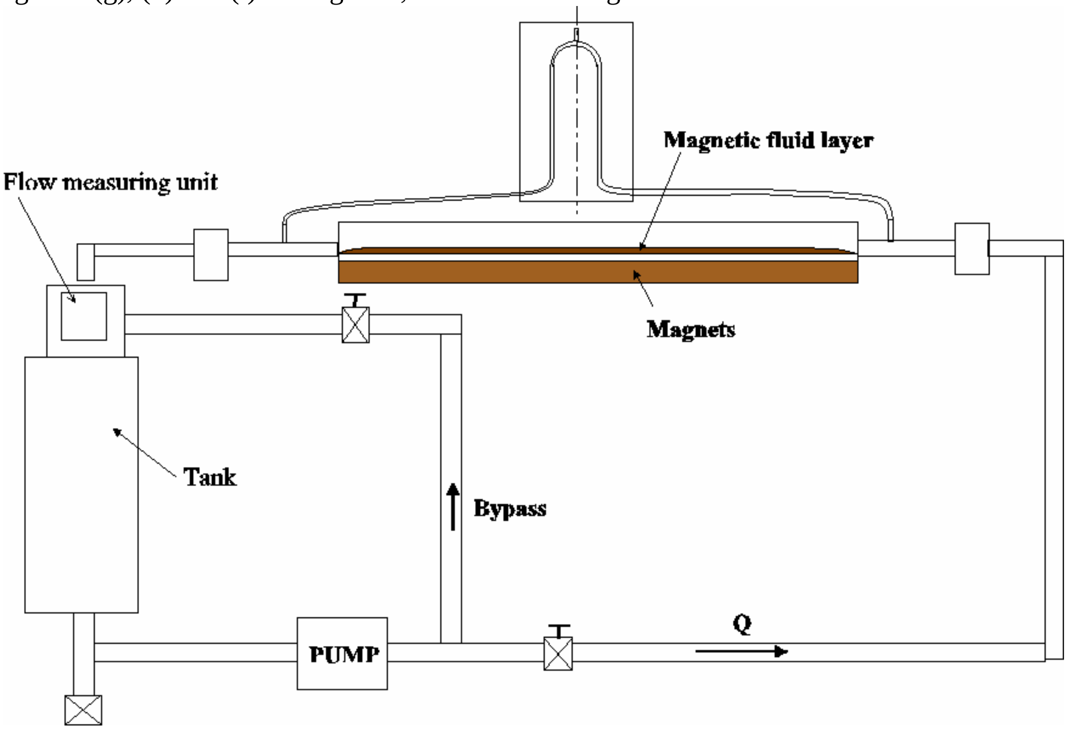


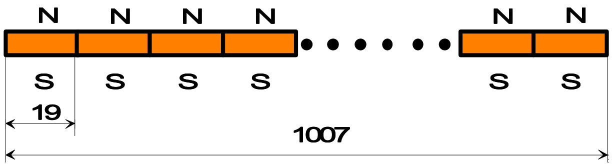
Figure 1 Experimental rig

A water-based ferrofluid (Ferrotec EMG805), kinematic viscosity 1.69cSt, density 1180 kg m^{-3}, was employed to form a magnetic fluid layer on the bottom of the duct. A silicone oil with a kinematic viscosity of 50cSt and density 960 kg m^{-3} was used for the main flow, resulting in a viscosity ratio of 29.4. The interfacial tension between the two fluids was 3.7 mN m^{-1}, and the ambient temperature was about 20°C.

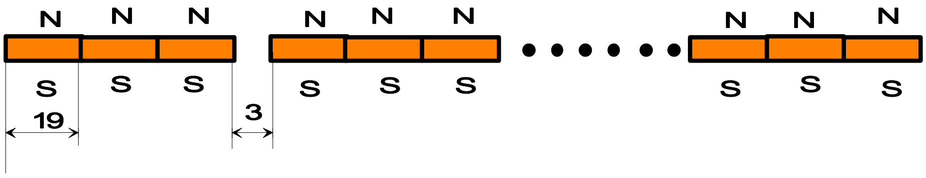
3.1 Influence of flow rate on shapes of interfaces

Figure 3 shows a set of sample pictures of the magnetic fluid layer at different flow rates in a magnetic field using the dense same-pole arrangement of magnets shown in Figure 2(a). The observations for the other arrangements showed qualitatively similar results. The narrow wavy black areas in the pictures are areas occupied by the magnetic fluid. The magnetic fluid layer was fairly uniform at zero flow rate but even at very small flow rates, it was strongly deformed into a bulge towards the outlet end substantially reducing the cross-section available for the main flow.

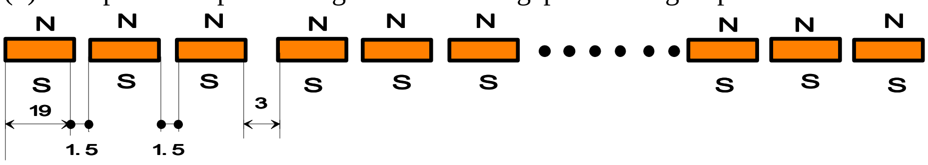
At low flow rates, all the magnetic fluid was retained in the duct but at higher flow rates some was carried out of the section. On increasing the flow rate from a steady state, magnetic fluid was removed from the layer until a new stable layer was formed. At a flow rate of 4.73 ml s^{-1}, only a small amount of magnetic fluid was retained in the duct at the outlet of the testing section. The stable layer configuration depended not only on the flow rate but also on the initial shape of the interface. When a thin uniform magnetic fluid layer was established at zero flow rate, the resulting layers rapidly became very thin, and were removed completely at relatively low flow rates. When the amount of magnetic fluid was less than a threshold value in each magnetic field, a continuous magnetic fluid layer could not be obtained because of the effects of interfacial tension.



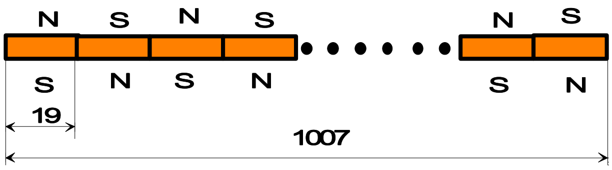
(a) Same pole arrangement with no gap between adjacent magnets



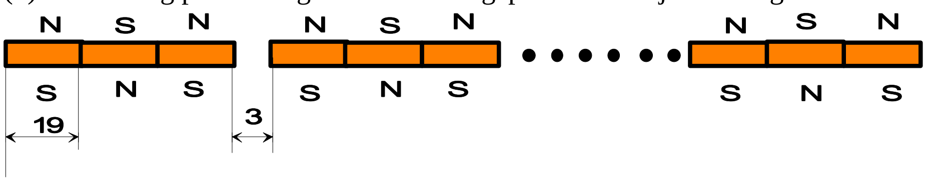
(b) Grouped same pole arrangement with no gaps in each group



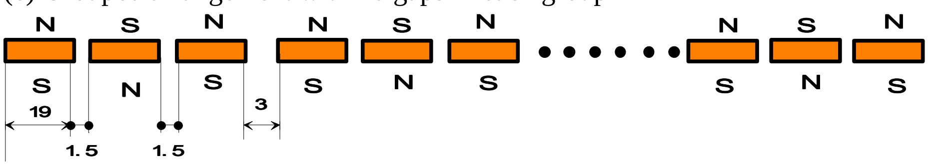
(c) Grouped arrangement with gaps in each group



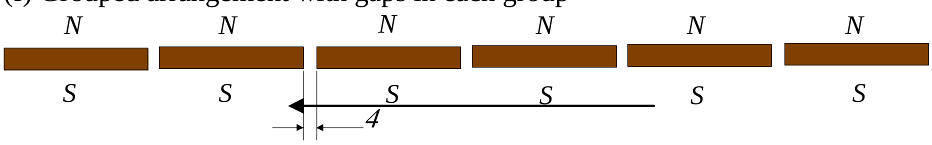
(d) Alternating pole arrangement with no gap between adjacent magnets



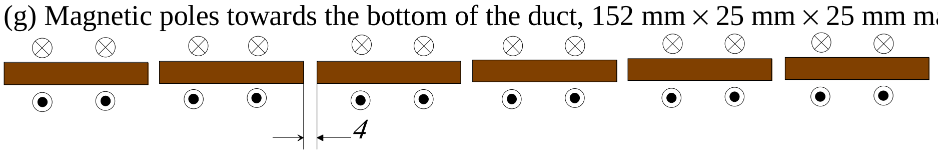
(e) Grouped arrangement with no gaps in each group



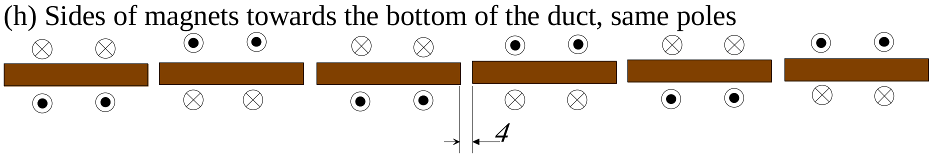
(f) Grouped arrangement with gaps in each group



(g) Magnetic poles towards the bottom of the duct, 152 mm × 25 mm × 25 mm magnets



(h) Sides of magnets towards the bottom of the duct, same poles



(i) Sides of magnets towards the bottom of the duct, alternating poles

Figure 2 Arrangements of magnets

3. INTERFACE SHAPES

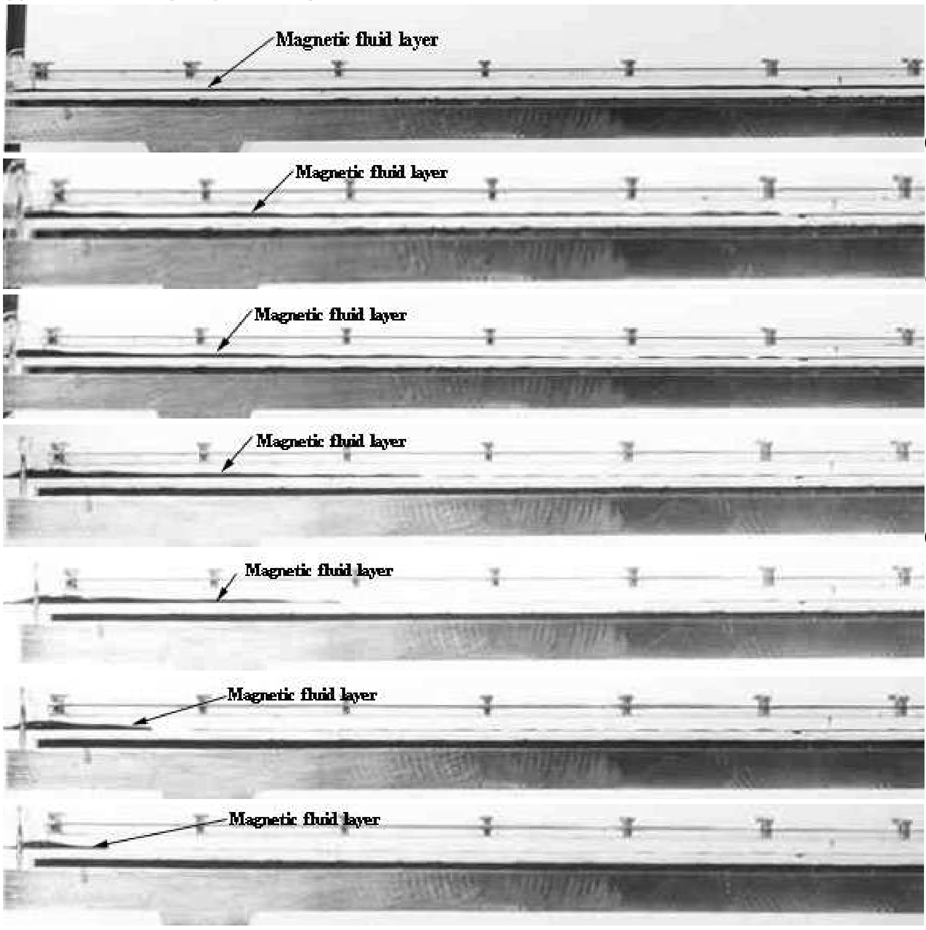


Figure 3 Sample pictures of the magnetic fluid layer, magnet arrangement as in Figure 2 (a)

3.2 Influence of magnetic field strength

To observe the influence of the strength of the magnetic field, we used the combination of magnets shown in Figure 2(d) with both, single and double layers of magnets . Figure 4(a) gives a sample picture of the shape of the magnetic fluid layer when one layer of magnets was applied, and Figure 4(b) is for the case when two layers of magnets were used. It can be seen that even though the flow rate over the stronger field was slightly higher, the length of the magnetic fluid layer was still longer than that over the weaker field. This indicates that stronger magnets were better at holding the magnetic fluid layer. It is well known, however, that too strong a field would result in a surface instability, known as normal-field instability[6], leading to the formation of ridges or even sharp spikes at the interface which would result in large energy losses. Our set-up did not suffer this type of instability.

(a) Q= 4.66ml s^{-1}, one layer of magnets (b) Q= 5.20ml s^{-1}, two layers

Figure 4 Influence of the strength of magnetic field, magnet arrangement as in Figure 2 (d)

3.3 Influence of magnetic field gradient

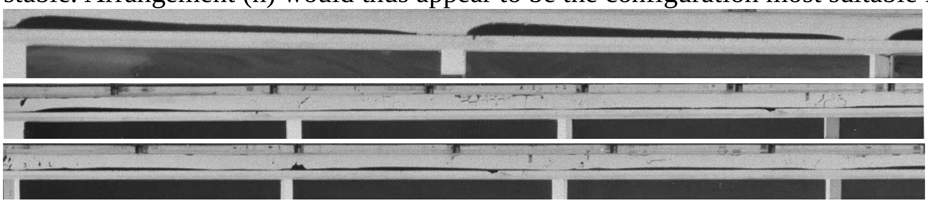
The gradient of the magnetic field can be changed, while keeping the maximum field strength constant, by adjusting the gaps between two adjacent magnets. Figure 5 gives two examples at similar flow rates where the gradient of the magnetic field in Figure 5(a) was smaller than that in Figure 5(b). The arrangement of the magnets for Figure 5(a) was that of Figure 2(e) where three magnets with alternating polarities sat closely together in a group. In Figure 5(b), the three magnets were separated by a small gap (3 mm), resulting in the arrangement indicated in Figure 2(f). It can be seen that the small gap between two adjacent magnets made the film longer and thinner at similar flow rates. The gaps increased the magnetic field gradient in the vertical and horizontal directions and reduced the strength of magnetic field in some areas. This indicates that a greater magnetic field gradient in the vertical direction gave a more uniform magnetic fluid layer. It is obvious that the gaps should not be increased too much, as the strength of the magnetic field between two adjacent magnets may become too weak to hold the magnetic fluid.

(a) Q= 6.50 ml s^{-1} (b) Q= 6.80 ml s^{-1}

Figure 5 Influence of magnetic field gradient, magnet arrangements as in Figure 2 (e) and (f), respectively.

3.4 Influence of magnetic field alignment

Figure 6 shows three sample interface shapes for arrangements (g), (h) and (i) at the same flow rate. While arrangement (g) is similar to the previous arrangements in that the poles face the fluid layer, the magnets in the other arrangements were aligned in the cross-channel direction. As a result, the field lines were approximately parallel to the interface rather than perpendicular to it. Not only was more magnetic fluid left in arrangement (g) than in the other two arrangements, but the head was also much thicker. Arrangements (h) and (i) were able to produce smoother interfaces than other arrangements. Leaving the experiment to run for more than five hours showed that the layer in arrangement (i) was gradually eroded while the layer in arrangement (h) appeared to be stable. Arrangement (h) would thus appear to be the configuration most suitable for further investigation.

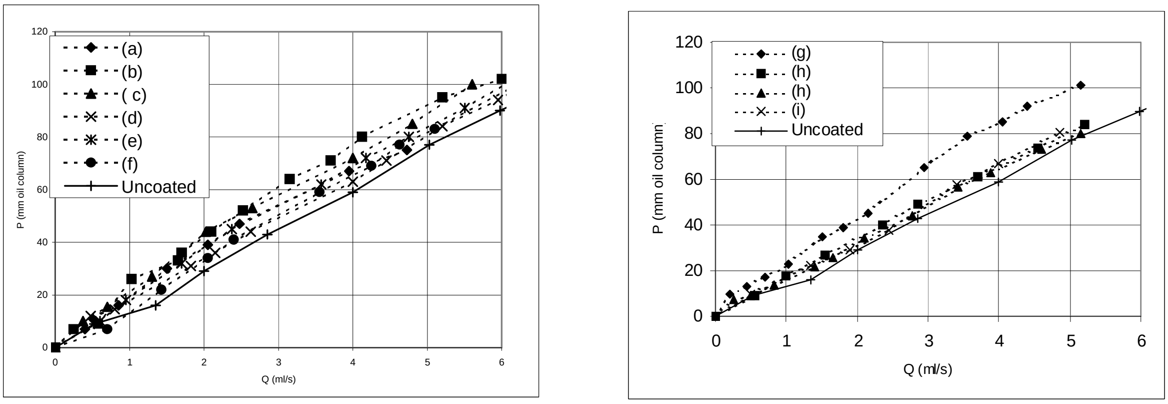


(g)
(h)
(i)

Figure 6 Sample pictures of the interface shape of magnet arrangement as in Figure 2 (g), (h) and (i), respectively, at Q= 3.50 ml s^{-1}

4. PRESSURE DROP

Figure 7 shows the pressure drop in the test section against flow rate in the different magnetic fields. The vertical axis is the pressure drop over the test section measured as the difference in column height of the silicone oil in the static head tubes, while the horizontal axis is the volume flow rate of the silicone oil through the duct. The measurements are given for the steady state which was reached when no more magnetic fluid flowed out from the magnetic fluid layer following an increase of the flow rate. Curves labelled '(a) to (i) arrangements' correspond to the different arrangements of the magnets listed in Figure 2, and 'uncoated' refers to the pressure drop when there was no magnetic fluid coating in the duct. It can be seen that all the coated ducts had larger pressure drops than the uncoated duct. Drag forces on the viscous fluid were actually enhanced not reduced. Magnetic fields (h) and (i), which are characterised by the largest vertical field gradient, gave the smallest increase in pressure drop while arrangement (g) gave the largest increase. As outlined in section 3.3, a larger vertical field gradient resulted in a flatter layer and thus a smaller obstacle to the flow. Consistent with this, the arrangements resulting in the most uniform (and thereby flattest) layers resulted in the smallest pressure drop increase. Though arrangements (h) and (i) led to nearly the same increment in the pressure drop, only arrangement (h) is suitable for further investigation because arrangement (i) led to interfacial instabilities at the ends of the magnets, which eventually broke up the magnetic fluid layer into small sections.



(a) 25 mm × 19 mm × 6 mm magnets (b) 152 mm × 25 mm × 25 mm magnets

Figure 7 Pressure drops in testing section; (a) to (i) refer to the arrangements of magnets shown in Figure 2, while 'uncoated' refers to the situation when no ferrofluid was present in the duct.

The magnetic fluid layer had three effects on the pressure drop. One was the reduction of shear stress due to the presence of a low-viscosity fluid at the solid boundaries. The second was that a ferrofluid layer occupies some of the cross-section of the duct, thereby reducing the cross-section available for the main flow. The third effect was that the non-uniform magnetic fluid layer and the pressure drop along the duct due to the flow of the silicone fluid deformed the interface, with a substantial obstruction and subsequent expansion of the available cross-section at the downstream end of the ferrofluid layer. Any fluid expansion results in energy losses or an increase in the pressure drop. While the first effect would reduce the energy losses, the latter two effects would increase them. When the first effect is stronger than the sum of the second and third effects, drag on the main flow can be reduced. Otherwise, the drag is increased. Increasing the viscosity ratio, reducing the thickness of the magnetic fluid layer, and smoothing the magnetic fluid layer could result in a net real drag reduction. In engineering applications, however, there are limits on the viscosity ratio and the minimum layer thickness for a particular fluid, and it is possible that the drag reducing effect may never outweigh the sum of the drag increasing effects.

5. CONCLUSIONS

An experimental study was carried out to investigate the effects coating a duct with a magnetic liquid layer and its effect on the friction losses in fluid flow through the duct. It was observed that it was possible to maintain a stable magnetic fluid layer for a range of flow rates of the main fluid through the duct. The shape and volume of the stable magnetic fluid layer, however, depended on the flow rate through the duct. A strong field with a high gradient was better suited than a weak and uniform magnetic field to hold the magnetic fluid as a layer on a surface. Due to the competing effects of drag reduction, by reducing the wall shear stress, and of drag increase, by narrowing the duct, it was observed that no overall drag reduction could be achieved in the experiments for a viscosity ratio less than about 30. Considering the results, it is anticipated that few engineering applications exist in which an actual drag reduction could be found, let alone be cost-effective.

The presence of a magnetic fluid layer on a surface, however, may prove a valuable device to enhance heat transfer. Even a simple visual inspection revealed a flow of the magnetic fluid at the interface from the tail of the magnetic fluid layer to the head. From consideration of mass continuity, it is easy to visualise that a ferrofluid circulation had been set up in the magnetic fluid layer. This flow field, together with the generally large thermal conductivity of the ferrofluid, might be an effective way of enhancing heat transfer between the fluid and the duct walls. This will be the subject of a future study.

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